COST-BENEFIT ANALYSIS OF A NOTIONAL FRACTIONATED SATCOM ARCHITECTURE*

O. Brown**
Defense Advanced Research Projects Agency

P. Eremenko† and C. Roberts‡
Booz Allen Hamilton

INTRODUCTION

The basic functions of a typical satellite, distilled to their quintessence, include only the absorption, processing, and subsequent re-radiation of photons. To this end, spacecraft components need only be able to exchange energy – which tends to be dichotomized into power and information – and transmit the occasional force or torque. Perfectly adequate and efficient mechanisms for accomplishing both of these tasks without resorting to a connecting solid structure exist.[i] Perhaps the most philosophically satisfying consequent view of a spacecraft is as a cloud of microstructural components – "pixie dust" – which may or may not be molecularly bonded to each other, contingent only on consideration of some appropriate overall system measure of merit. It is the aim of this analysis to construct such a measure of merit, and to assess its implication for the optimality of various architectures.

Philosophical appeal notwithstanding, we must, by necessity, commence our inquiry by considering the status quo. Thus, consider a monolithic satellite designed to deliver some service to the user. We define the number of similar and dissimilar modules in which this spacecraft is fractionated as the homogeneous and heterogeneous degree of fractionation, respectively. A monolithic spacecraft has a homogeneous and heterogeneous degree of fractionation of unity. We define the measure of merit for a particular architecture in dollar terms as the value (benefit) delivered to the user minus the total cost expenditure over the entire life cycle of the system. The vast majority of the intellectual energy underlying this analysis is expended on exhaustively quantifying all sources of value delivered by the system that are likely to scale with fractionation.[ii]

Four such value sources are identified. They include the intrinsic value of the service or capability offered by the space system (e.g., value of a unit of bandwidth, value of a unit of area of coverage, or value of a certain number of pixels of resolution on a target); the value to the user derived from incremental deployment and graceful deterioration of capability due to on-orbit failures or hostile actions; the value to the user derived from the flexibility to increase service levels in response to increased demand throughout the

** Program Manager, Tactical Technology Office. E-mail: owen.brown@darpa.mil.

† Associate, Defense Business Segment. Corresponding author: Booz Allen Hamilton Inc., 3811 North Fairfax Drive, Suite 600, Arlington, Virginia 22203, tel: (703) 816-5492, fax: (703) 816-5444, e-mail: eremenko_paul@bah.com.

‡ Senior Consultant, National Security Business Segment. E-mail: roberts_christopher@bah.com.

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lifetime of the system; and the value to the user from reduction in the lifecycle cost risk. Recognition of some of these value sources is not an entirely novel insight. Recent analyses, for instance, have recognized the value of incremental deployment and flexibility associated with variable service levels for space constellations.[iii] A highly simplified cost model is utilized. The historically-based cost scaling with mass is only sophisticated enough to be able to capture the efficiency penalties or gains associated with “wireless” versus “structural” coupling of the spacecraft modules, and to incorporate relevant learning curve effects.

The real objective of this analysis is not so much to arrive at a precise quantification of the value proposition and cost expenditures for a particular architecture, as it is to outline a methodology – demonstrated in the context of a notional architecture – which may then be applied during the preliminary design phase of an actual space system.

SYSTEM ARCHITECTURE

The input to the cost and value models is the time history of the on-orbit system architecture, i.e., the number of operational modules of each module type. Two phases of the system lifetime are considered. During the deployment phase the relevant parameters are the launch rate and production rate. The number of successful launches is modeled as a random variable with a negative binomial probability distribution. During the operational phase, once the modules constituting the entire system have been launched, on-orbit failures are modeled as a Poisson process. Additionally, a scenario with a massive failure – that of a large number of modules – is modeled.

In addition to the inescapable myriad of simplifications and assumptions underlying each component of our model (detailed in the appropriate section), we must make some general assumptions to limit the scope of the task at hand. We elect a satellite communications (SATCOM) mission as the strawman for our analysis. There are several reasons why SATCOM is particularly well-suited for this purpose. First, it is the archetype of a photon-reflection mission. Second, it has a roughly linear capability function (capability is proportional to number of transponders). Third, there is a commercial SATCOM market which allows the calibration of our utility model to dollar terms. And fourth, the generally unclassified nature of the data on DOD’s SATCOM requirements and use readily lends it to statistical analysis of user demand fluctuations.

We make the assumption that the modules resultant from fractionation are of roughly equal size. This is a strong assumption. To compensate for the obvious architectural limitations which it may impose, a scaling matrix – requiring that an operational capability requires a correspondence other than 1:1 between heterogeneous module types – may easily be incorporated. For the sake of clarity and simplicity we avoid doing so and essentially assume that the homogeneous degree of fractionation is identical for each of the heterogeneous module types (and that on-orbit spares are not utilized).

Finally, we assume that the lifetime of the system is fixed and is sufficiently large that the variance in the capability metrics introduced during deployment is negligible when averaged over the entire lifetime. Selecting and optimizing the lifetime of complex engineering systems in general, and space system in particular, has been the subject of some recent and rather sophisticated analyses[iv] which are relevant, but beyond the scope of the present investigation; technology obsolescence effects are also neglected.

VALUE MODEL

The objective of the value model is to associate, in dollar terms, the "benefit" delivered by the system to the user over its lifetime with a given system architecture. Consequently, the input is the time history of the number of modules of each type on orbit. The first step is to map this raw architectural description into system capability metrics. The metrics selected for the notional SATCOM mission in this analysis are bandwidth and availability. The second step is to map these two capability metrics to an overall system utility metric on the basis of the relative importance that users attach to one capability attribute versus the other. The overall system utility is a dimensionless ordinal which is then translated into dollar terms by an appropriate calibration using existing commercial SATCOM service valuations. Note that the service value generated by the on-orbit architecture varies in time; it is modeled as a series of discrete cash flows which are taken to present value and summed. A volatility for the monetary value of the satellite service is estimated based on the variance in the service level due to on-orbit and launch failures and based on projections for the variance in the DOD's demand for SATCOM bandwidth.

Another piece of the value model is the value derived from a reduction in the cost risk due to fractionation. This value increment is priced by using the self-insurance analogy and the historical industry insurance premiums. The volatility in insurance premiums is also a contributor to the overall volatility of the value derived. In light of this volatility in value, the flexibility of tailoring the service level to increased demand at any time during the life of the system is represented by a real option. The price of the option – the value of the flexibility – is added to the previously determined service and cost risk reduction value, thereby completing the value model.

Mapping Architecture to Capability

The SATCOM mission, as previously mentioned, was chosen in no small part due to the simplicity of its capability function. The capability function is linear; the primary service level metric – bandwidth or, equivalently, coverage area – scales in proportion to the number of transponder modules. Therefore, mapping the on-orbit architecture to a capability metric is a fairly trivial exercise. Here, in addition to bandwidth, we also introduce an availability capability metric which is intended to be reflective of the frequency with which the communication service is degraded. In a monolithic system, availability is trivial to compute: it is literally the fraction of the time the service is available. A fractionated system experiences graceful degradation of service as

individual payload modules become inoperative (either because of their intrinsic failure, or loss of power or other vital functions provided by another module). Consequently, the definition of availability metric is in terms of the variance of the overall system bandwidth.

$$bandwidth(t) \sim \min\left(n_1(t), n_2(t), \ldots, n_k(t)\right)$$
$$availability(t) \sim \left(1 - \frac{\sigma_{bandwidth}(t)}{bandwidth(t)}\right)$$

An entirely general formulation would include arbitrary multiplicative scaling constants for the quantity of modules of each type. By assuming all these constants equal to unity, the implicit assumption that a single module of each type is needed to provide one payload module worth of capability is made. This is a fairly dramatic simplification that ought to be eschewed in a rigorous cost-benefit analysis for a specific system. We take the liberty, however, in the interests of expositive clarity.

Mapping Capability to Utility

An efficient market (in the strict economic sense) is, without a doubt, the ideal means by which to discern user preferences and value a particular service offering. In the absence of such a market, however, as is the case with military SATCOM services, we must go directly to the user and attempt to deduce his preferences by cleverly constructed queries that mitigate any bias in the responses.

One such method of overcoming the problem of valuing non-market based attributes comes from the field of decision theory. Von Neuman and Morgenstern[v] devised a systematic method of measuring decision maker's preferences for outcomes under conditions of uncertainty known at utility theory. Keeney and Raiffa[vi] expanded this work to enable the treatment of multiple attributes. This technique, known as Multi-Attribute Utility Theory (MAUT),[vii] provides a means for constructing a function composed of many single-attribute utility functions and a relative weighting coefficients among the single-attribute utility functions. The weighting coefficients provide a good indication of the relative importance between the attributes. If one attribute can be tied to a reasonably well defined market value (in dollars) then it is possible to relate the value of non-market based attributes based on the relative magnitude of the weighting coefficients. In this study we infer the value of availability from the relative multi-attribute weighting coefficient of communications bandwidth – a marketable commodity.

To establish single attribute utility functions Von Neuman and Morgenstern impose the following conditions:

- Existence of preference and indifference: The decision maker has preferences.
- Transitivity: If the decision maker prefers A_0 to A_1, and A_1 to A_2, then A_0 is preferred to A_2.

- Substitution: If the decision maker is equally happy with either of two certain outcomes, then he/she is also willing to substitute one for the other in a lottery.
- Archimedean: The decision maker will always accept a lottery between the best and worst outcome in preference to a sure intermediate outcome, provided the probabilities are adjusted properly.

For multi-attribute considerations the following conditions must also hold:

- Preferential independence: The preference of one subset of attributes over another subset of the same attributes is independent of the level of other attributes (i.e., (A_1,B_1) preferred to (A_2,B_2) independent of the value of attributes C, D, E, …, etc.).
- Utility independence: The shape of the utility function of a single attribute is independent of the level of the other attributes. This condition is more stringent than preferential independence and allows the construction of a multi-attribute utility function from many single attribute functions.

Utility functions (and the conjoining multi-attribute utility function) are elicited from the decision maker in a formal interview. Many techniques exist for eliciting utility functions, however Hershey & Schoemaker[viii] and others have shown that some techniques result in experimental biases. To reduce these biases, deNeufville[ix] and Delquie[x] recommend a lottery equivalent probability approach (LEP). The LEP technique was implemented for this study employing a software program developed by Delquie known as ASSESS. A detailed description of the lottery equivalent probability technique can be found at the end of this section.

Another technique for reducing bias in the interview process is to frame the attribute scenarios outside of their nominal context. This keeps the decision maker focused on the value-delivering attributes as opposed to the technical point solution that achieves them. That is, the decision maker is making choices about the customer requirements as opposed to the technical or system requirements. Below are the attribute scenarios employed in this study.

<u>Bandwidth Scenario:</u> An advanced antenna/electronics package has become available that may transmit bandwidths up to 100 Mbps. However, antenna/electronics packages may be knocked out of alignment during launch, reducing the operational bandwidth. Your design team has studied the issue and determined that the advanced antenna/electronics package has a P chance of providing bandwidth at 100 Mbps or a 1-P chance of providing bandwidth at 1 Mbps, while a traditional design will give you a 50% chance of getting data at D Mbps or 1 Mbps.

<u>Availability Scenario:</u> A new network server has just come to market that is extremely robust to interruptions in service that are commonly caused by crackers. If you were to adopt these advanced servers there is a chance you could communicate your mission-critical information with 100% availability. However, there is also a chance that crackers

could exploit an unknown vulnerability in the advanced servers that may lead to a reduction in availability. Your design team has studied the issue and determined that the advanced servers have a P chance of providing 100% availability or a 1-P chance of providing availability at 10% (i.e., the network is completely unavailable), while traditional servers will provide a 50% chance of availability at A% or 10%.

<u>Assessing Single Attribute Utility Functions:</u> To assess each point on the bandwidth single attribute utility curve, a technique known as bracketing is used. This method elicits the interviewee's risk profile by honing in on an indifference point (i.e. the point at which the interviewee is indifferent between Scenario A and Scenario B). Although the interviewee could simply specify the probability at which indifference occurs at the outset, bracketing has been experimentally shown to reduce bias in the interview process.

We replicate portions of a sample interview below.

1) Which of the following situations do you prefer?
Situation A) 38% chance of getting 100 Mbps & 62% chance of getting 1 Mbps
Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation A is chosen.

2) Which of the following situations do you prefer?
Situation A) 10% chance of getting 100 Mbps & 90% chance of getting 1 Mbps
Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation B is chosen.

Note that in Situation A the probability of getting the best outcome was less than in question #1. Situation B is chosen over Situation A, thus "bracketing" the indifference point between 0.38 and 0.10.

3) Which of the following situations do you prefer?
Situation A) 31% chance of getting 100 Mbps & 69% chance of getting 1 Mbps
Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation A is chosen.

4) Which of the following situations do you prefer?
Situation A) 15% chance of getting 100 Mbps & 85% chance of getting 1 Mbps
Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation B is chosen.

5) Which of the following situations do you prefer?
Situation A) 27% chance of getting 100 Mbps & 73% chance of getting 1 Mbps

Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation A is chosen.

6) Which of the following situations do you prefer?
Situation A) 18% chance of getting 100 Mbps & 82% chance of getting 1 Mbps
Situation B) 50% chance of getting 51 Mbps & 50% chance of getting 1 Mbps

Situation A is chosen.

We have thus bracketed the indifference value for a given point on the bandwidth single-attribute utility curve within a specified tolerance (i.e., 3%). Now we assess the second point on the bandwidth single attribute utility function.

1) Which of the following situations do you prefer?
Situation A) 13% chance of getting 100 Mbps & 87% chance of getting 1 Mbps
Situation B) 50% chance of getting 26 Mbps & 50% chance of getting 1 Mbps

Situation A is chosen.

For the second point on the utility curve, the bandwidth value in Situation B has changed. This process continues for each point. The researcher is free to determine the number of points to evaluate. Once the complete single attribute utility function is defined, the process is repeated for all attributes – in this case with the addition of availability.

The resultant single-attribute utility functions for a baseline set of interviews were taken to be:

$$u(bw) = -1.61 + 1.60 \cdot \exp\left(\frac{-bw}{-205.1}\right)$$

$$u(av) = 1.001 - 2.03 \cdot \exp\left(\frac{-av}{14.16}\right)$$

based on exponential curve fits typically utilized in this application. The variable *bw* is taken to represent bandwidth in Mbps and the variable *av* is availability in percent of time. The unrealistic behavior of these functions at the low and high extremes is reflective of the limited range of bandwidth and availabilities over which the interviews were conducted.

Assessing the Multi Attribute Utility Function: The multi-attribute utility interview elicits the interviewee's weighting among the attributes. To determine the multi-attribute utility function the first set of questions will consider Situation A, which offers a scenario of the best bandwidth value & worst availability value against a changing probability in Situation B. Once again, samples are reproduced below.

1) Which of the following situations do you prefer?
Situation A) 100 Mbps Bandwidth & 10% Availability with certainty
Situation B) 25% chance of getting 100 Mbps Bandwidth & 100% Availability (Best, Best) AND 75% chance of getting 1 Mbps Bandwidth & 10% Availability (Worst, Worst)

Situation B is chosen.

2) Which of the following situations do you prefer?
Situation A) 100 Mbps Bandwidth & 10% Availability with certainty
Situation B) 20% chance of getting 100 Mbps Bandwidth & 100% Availability (Best, Best) AND 80% chance of getting 1 Mbps Bandwidth & 10% Availability (Worst, Worst)

Situation B is chosen.

3) Which of the following situations do you prefer?
Situation A) 100 Mbps Bandwidth & 10% Availability with certainty
Situation B) 10% chance of getting 100 Mbps Bandwidth & 100% Availability (Best, Best) AND 90% chance of getting 1 Mbps Bandwidth & 10% Availability (Worst, Worst)

Situation B is chosen.

An indifference point is thus achieved. Subsequent interview questions compare Situation A, which offers a scenario of the worst bandwidth value and best availability value, with the questions repeated in the same format.

The resultant multi-attribute utility function is of the form:

$$U(bw,av) = K \cdot k_{bw} \cdot k_{av} \cdot u(bw) \cdot u(av) + k_{bw} \cdot u(bw) + k_{av} \cdot u(av)$$

A representative set of coefficients based on some notional interviews is as follows:

$$K = 1.53$$
$$k_{bw} = 0.07$$
$$k_{av} = 0.84$$

Note the underlying implication that availability is far more important to the baseline stakeholder group than is bandwidth.

Mapping Utility to Value of Service

Utility, as indicated previously, is a dimensionless metric which allows the comparison of multiple architectures, but is not directly comparable to cost – as is the objective of a cost-benefit analysis. The existence of a market for commercial SATCOM services, and the military's frequent reliance on commercial services for its own use, however, permits the mapping of utility to dollar terms based on one or more service architectures for which market value is known and utility may be computed given its average system availability and transponder bandwidth capabilities. Since the utility scale is a cardinal one, we make the assumption that the intensity of preferences represented by the utility function enables a mapping of the utility scale to into market value, and that the mapping is a linear one.

For a comprehensive analysis of DOD use of commercial SATCOM we draw upon the excellent study authored by Tim Bonds et al. of the RAND Corporation.[xi] In addition to basic demand projections for satellite communication services, we are also interested in the volatility associated with the service levels. It is helpful to subdivide the contributions to the volatility (equivalently known in this context as variance or risk) of value according to their source. There is a component due to the volatility of the supply and another due to the volatility of the demand for the service provided. The volatility of the supply stems from variability of the orbital architecture and resultant service capability. This component of variance, therefore, is diversifiable – i.e., it can be reduced by increasing the degree of fractionation. The variance due to changes in the demand, on the other hand, is the non-diversifiable component of volatility in the value metric; it is a result of changes in the geo-political and commercial climate within the market for the service. At a macroscopic scale these changes are essentially random (a diffusion process, to be precise) in character with some aggregate average drift.

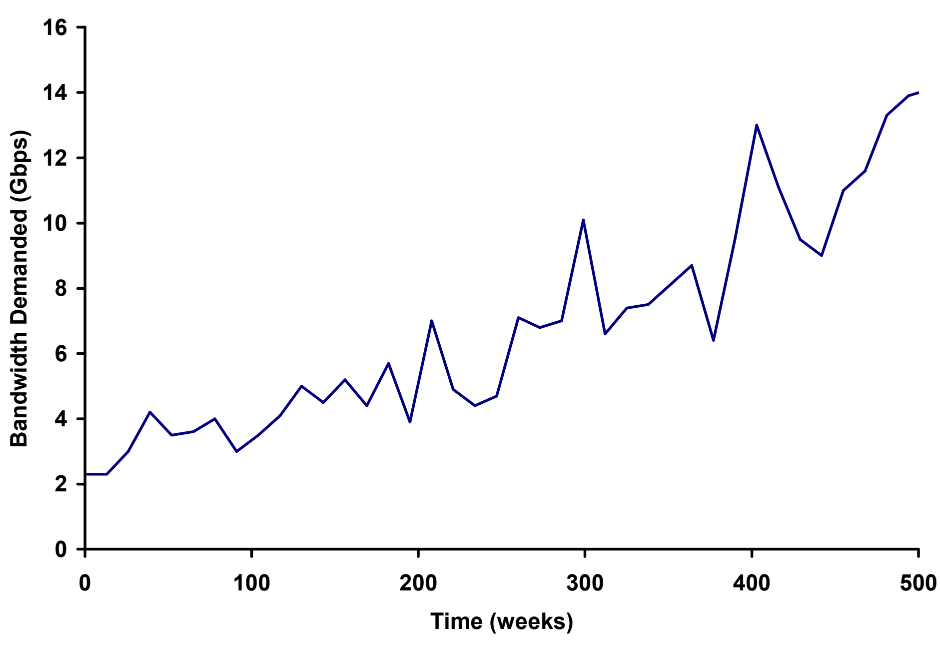

Figure 1: Notional DOD SATCOM demand projections. Based on Bonds et al. (ref. xi).

The volatility of supply is directly computable from the model presented here (i.e., it is essentially the system availability metric introduced previously). The volatility of demand, on the other hand, must be estimated based on historical data (or, alternatively, based on behavioral models of market players – an approach that is intriguing but far beyond the scope of this work). We compute the volatility based on the model data in Bonds et al.[xii] The results, naturally, are specific to SATCOM architectures, but the overall approach is general.

Adding the Value of Reduced Cost Risk

Cost risk scaling for varying degrees of fractionation has previously been estimated by Brown.[xiii] That analysis, however, did not attribute a value to a given level of cost risk reduction. An enlightening analogy is that reducing cost risk by architectural means, such as fractionation, is effectively equivalent to self-insuring the system during its launch[xiv] and operations phases. Industry average insurance rates are available from the Department of Transportation[xv] and are shown in the figure below.

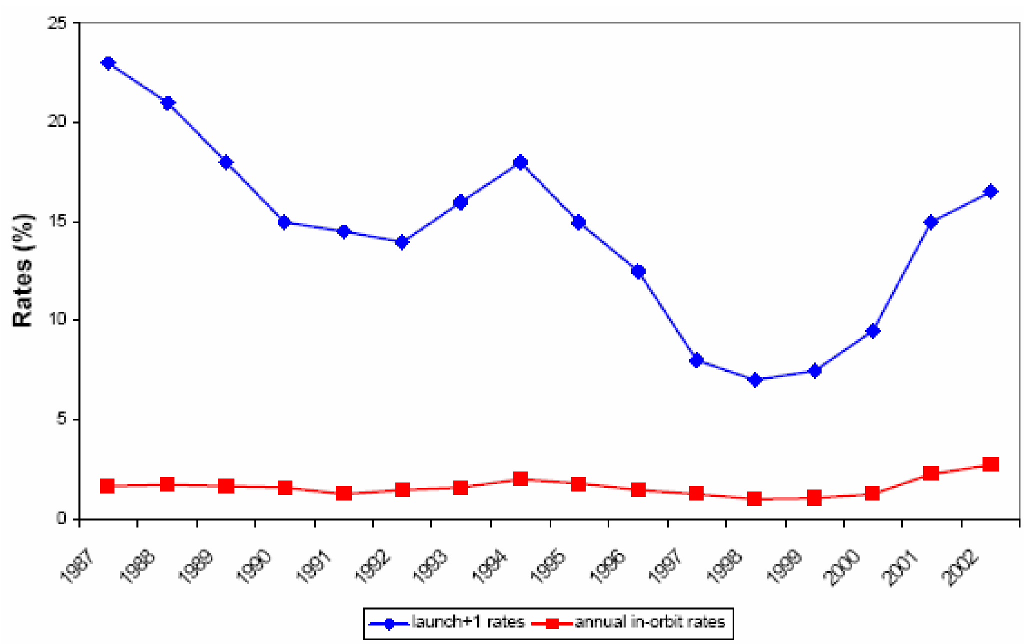

Figure 2: Industry-wide average insurance rates for launch plus one year of on-orbit operations (blue) and one year of orbital operations (red). Taken from DOT data [ref. xv].

Adding the Value of Flexibility

The quantitative valuation of flexibility is closely related to the valuation of financial derivative assets. Black, Scholes, and Merton, in their Nobel Prize-winning work three decades ago, developed a quantitative methodology – now widely known as the Black-Scholes Formula – for the valuation of financial options.[xvi] A financial option is essentially a right, but not the obligation, to buy or sell some underlying asset at a future time. Real options, in contrast to financial options, are the options to effect some real-world action, rather than buy or sell a financial security. The pecuniary

consequences of the real-world action are then treated as the underlying asset, and a Black-Scholes valuation can be performed to quantify the appropriate price of the real option.

Conceptually, the option is the flexibility to postpone into the future a particular decision until the uncertainty surrounding the potential outcomes of that decision is lower. Thus, whereas a stock option has value because it allows its owner to postpone the decision to buy (or sell) stock when the relative uncertainty of the stock's future value is lower, a real option to perform on-orbit satellite servicing for life extension, for instance, has value because it allows the deferral of the decision of whether or not to extend the satellite's lifetime from the design phase to a point when the satellite has been in operation for some time and its value to the user is better known.

A fractionated architecture gives the user the option of incrementally upgrading the capability should the demand change. It is well-established that such flexibility has value, and the relatively new theory of real options[xvii] has recently been proposed for the valuation of defense acquisition programs[xviii] and successfully applied to the quantification of analogous flexibility in other space system contexts[xix]. We model the option to upgrade any time throughout the system lifetime as the "real" analogue to an American call option. A Black-Scholes valuation of such an option is given below.

$$V_{American,Call}(t) = V_0 \cdot N(d_1) - C \cdot e^{-rt} \cdot N(d_2)$$

$$N(x) = \int_{-\infty}^{x} \frac{e^{-t^2}}{\sqrt{2\pi}} dt$$

$$d_1 = \frac{\ln \frac{V_0}{C} + (r + \frac{\sigma^2}{2})t}{\sigma\sqrt{t}}$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

Here, the value of the option is a function of V_0 – the initial value of the underlying asset (here, the satellite service metrics), C – the strike price or exercise price of the option (here, the cost of altering service level by deploying an additional module), r – the discount rate, σ -- the volatility of the underlying asset, and time, t. N(x) is the normal probability cumulative distribution function.

COST MODEL

Estimation of the various constitutive elements of space system cost is a well-developed (if not an exact) science. It is not the purpose of the present analysis to make any substantive innovations in this area, nor do we believe such advancements to be necessary for the accurate estimation of the costs of fractionated space systems. Consequently, in the interests of generality, we have chosen to apply empirical cost estimating relations (CERs) from the industry classic *SMAD*[xx] so as to refrain from making unnecessary assumptions about architectural details. Furthermore, operating

costs are assumed simply to be a small fraction of the overall life cycle cost, as per industry trends.

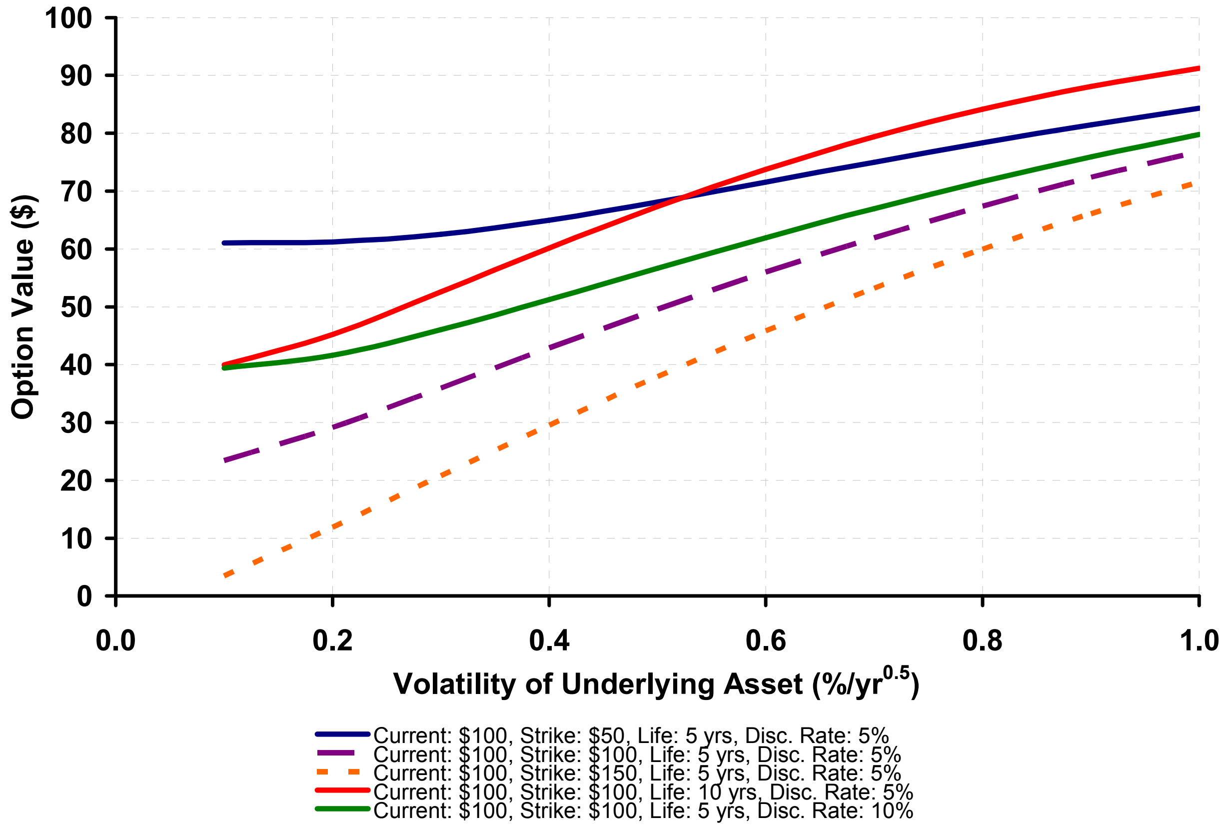

Figure 3: Illustration of the value of a call option as a function of various option parameters.

The salient cost behaviors in the recurring (RE) cost are captured by a multiplicative increment in recurring costs due to the mass penalty associated with component duplication due to fractionation, and production learning curve effects due to the multitude of similar modules. The two top-level components of the RE are the module 'payload' (whatever the specialized functionality of a particular module is) and the supporting module 'bus' (the common components across all modules that cannot be or are not fractionated). The NRE and launch cost estimates are computed straightforwardly assuming an aggregate fractionation mass penalty.

$$C_{RE} = C_{module} + C_{bus} = CER_1 \cdot \left(\frac{m_0}{\sum_{i=1}^{k} n_i} \right) \cdot N_{modules}^{\ln(2)/\ln(\gamma)} + CER_2 \cdot (\alpha - 1) \cdot \left(\frac{m_0}{\sum_{i=1}^{k} n_i} \right) \cdot \left(kN_{modules} \right)^{\ln(2)/\ln(\gamma)}$$

$$C_{NRE} = CER_3 \cdot \alpha \cdot m_0$$

$$C_{launch} = CER_4 \cdot \alpha \cdot \left(\frac{m_0}{\sum_{i=1}^{k} n_i} \right)$$

Where CER_j are cost estimating relation coefficients (essentially cost per unit mass of various subsystem types) which we have adopted from the literature, γ is the learning curve slope (around 0.85 for the aerospace industry) , m_0 is the mass of the equivalent monolithic spacecraft, $N_{modules}$ is the total number of modules that the spacecraft is fractionated into, α is the fractionation mass penalty factor, and n_i are the number of modules of type i, where i takes on values from 1 to k.

SAMPLE RESULTS

We present sample results that exercise the model described above for two scenarios. The first is the monolithic case which experiences an on-orbit failure event followed by a catastrophic failure event (in the monolithic case the two manifest themselves identically, but the distinction is important in the fractionated case which follows). The time history of the system cost and system value is plotted in Figure 4, below, in the red and blue, respectively. For future revenues and expenditures, the plots show their magnitudes in present value (PV). All NRE is assumed expended prior to the starting time, at week 0. The dashed line superposed on the plot references the right vertical axis which shows the time history of the number of modules that are on-orbit and operational (again, this is fairly trivial in the monolithic case).

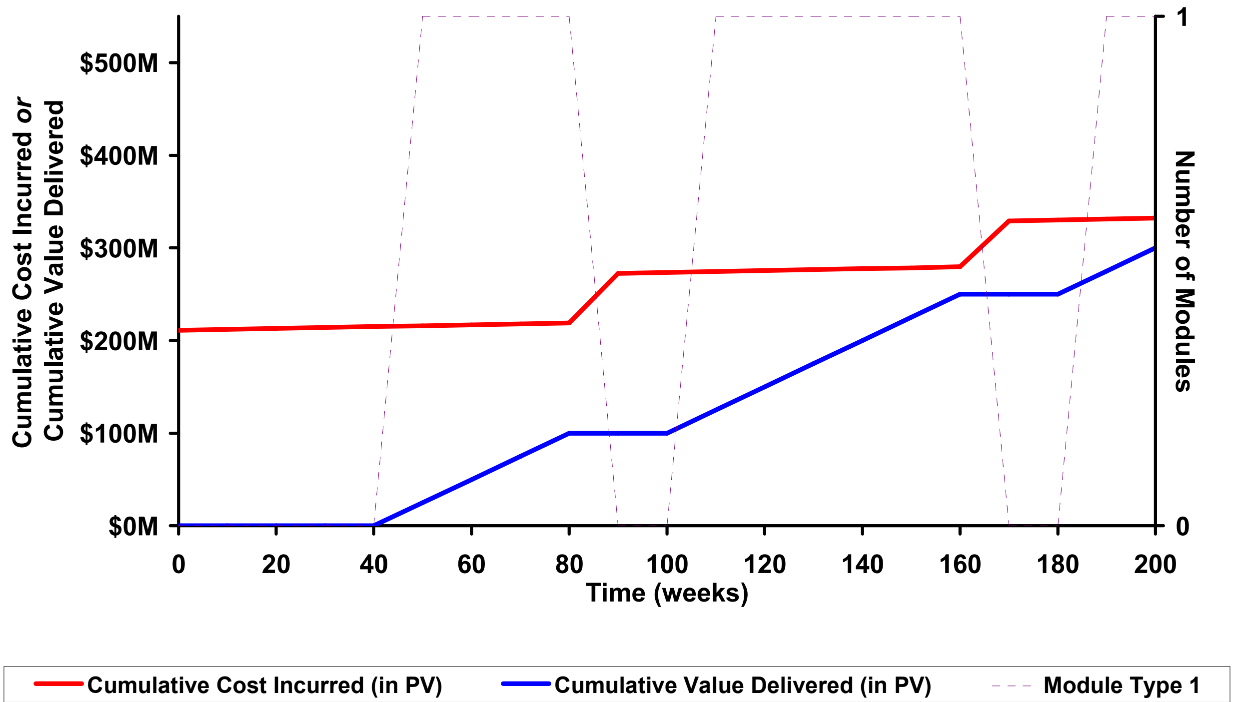

Figure 4: Example of the on-orbit evolution of a monolithic architecture.

Figure 5, in contrast, shows a notional fractionated architecture over a similar time span. The time histories of the number of deployed modules are now broken down for several module types (e.g., power, computation & data handling, and communications transponder); the small blips in each module types reflect individual failures (which are assumed to occur more frequently in the fractionated case to capture the traditionally decreased reliability associated with microsatellites); a catastrophic failure event is simulated at week 100. The fractionated modules are replaced with smaller lag times than in the monolithic case. It is also noteworthy that while the NRE for the fractionated system is higher, the system deteriorates gracefully and gradually in response to failures and even catastrophic events, and permits for the incremental operational deployment of capability (i.e., partial value earned before week 40).

It is also instructive to consider the various contributions to the cost and value histories shown in Figure 5. This breakdown is portrayed in Figure 6 which follows. Note that the examples in Figures 5 & 6 were specially contrived to mimic the scenario in Figure 4 but demonstrate that in spite of higher overall cost and mass, the overall cost-benefit proposition (i.e., the present value of total lifetime value delivered minus the lifecycle cost) may close (turn out positive) in the fractionated case and fail to close in the monolithic case. That is the true power of such an architecture.

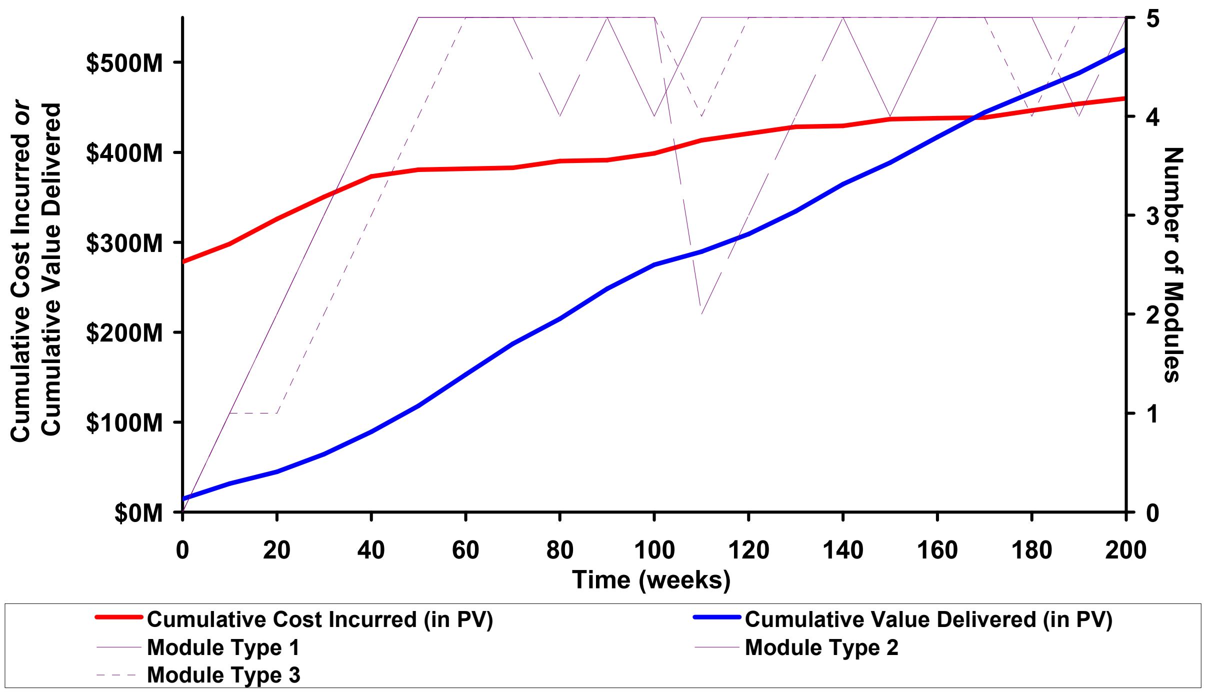

Figure 5: Example of the on-orbit evolution of a fractionated architecture.

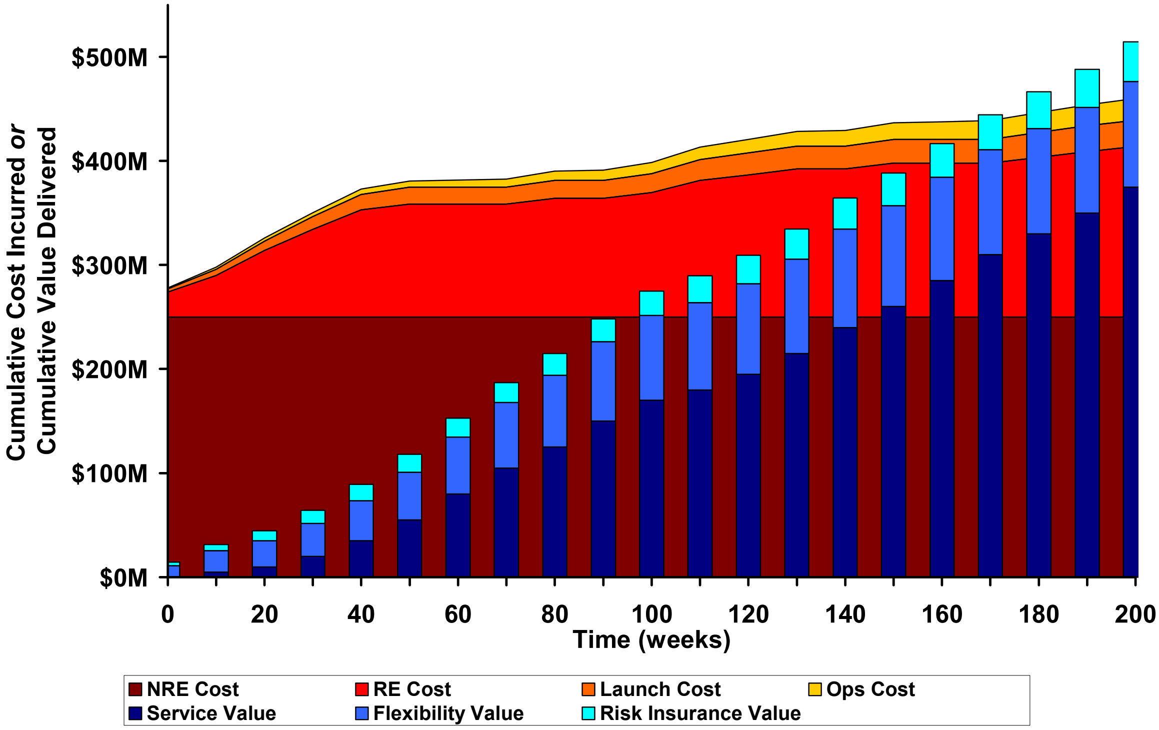

Figure 6: Sample cost and value breakdown for the time evolution of a fractionated architecture.

CONCLUSION

As the primary challenge in the development, deployment, and operation of space systems mature past simply trying to get the spacecraft to work and deliver a required capability, to the more mature and nuanced objectives of trying to refine the satellite design to incorporate robustness, flexibility, and economic efficiency, the set of tools by which the design process, acquisition strategy, and value proposition is constructed must also evolve. The tools, methodologies, and – perhaps most importantly – the mindset are still today very much biased towards large monolithic spacecraft with maximum reliability and lifetime. The successful transition to more innovative, agile, and economically sensible architectures will be predicated upon a paradigm shift in the approach to their design, acquisition, deployment, and operation. It was the objective of this analysis to provide the résumé of a methodology by which the impact of such a paradigmatic transformation may be contemplated.

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[ii] The astute reader will observe a duality of purpose here – leading to a slightly schizophrenic analysis. First, we wish to determine the optimum degree of fractionation for a given mission. This only requires the quantification of value and cost of a given architecture *relative to the monolithic architecture* for that mission. Thus, only those sources of value and cost impact that are different between a monolithic and fractionated system are need be identified and modeled. Our second aim, however, is to provide a cost-benefit analysis for a particular architecture with a specified degree of fractionation. This necessitates an exhaustive bookkeeping of all sources of value and cost whether they be different or identical for a fractionated and monolithic architectures. We focus our energy on the first objective, but believe that the resultant model comes fairly close to meeting the second.

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[xiv] The self-insurance analogy applies to the launch phase only if each of the modules of the fractionated system is launched separately. This is consistent with the subsequent assumption that a responsive space launch capability exists in the payload range that is essentially perfectly tailored to the module size. Self-insurance may also be accomplished by piggy-backing the individual modules on other payloads placed in orbit by larger launch vehicles. The only real requirement for self-insurance is that the random variables for the success or failure of each module's launch be independent.

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